Seismic Velocity Dispersion and the Petrophysical Properties of Porous Media

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Summary

Seismic attenuation and velocity dispersion depend on the petrophysical properties of porous media. Using broadband uncorrelated vibrator VSP data, we measure velocity dispersion in the exploration seismic frequency band with satisfactory accuracy. Then, velocity dispersion data are fitted to petrophysical models. This approach provides new insights into the linkage between velocity dispersion and physical rock properties of porous or fractured media.

Introduction

Seismic waves in anelastic rocks are distorted by attenuation and velocity dispersion of various mechanisms. Attenuation and velocity dispersion depend on petrophysical properties, e.g., porosity, fractures, and fluid fill. The causality of seismic wave requires that the linkage between velocity dispersion and attenuation is the Kramers-Krönig relation (Futterman, 1962). For example, in a constant Q model (i.e., Q is independent of frequency in a broad frequency band), seismic velocity increases approximately linearly to log frequency (Liu et al., 1976). This type of velocity dispersion can be referred to as linear velocity dispersion.

Research on attenuation and velocity dispersion includes modeling studies of different petrophysical models, e.g., partial gas saturation (White, 1975), squirt flow (Mavko, 1998), patchy-saturated porous media (Johnson, 2001), and random porous media with fluid flow (Müller and Gurevich, 2005). In these models, Q is frequency dependent. For example, Figure 1 shows an attenuation and velocity dispersion model of a random porous media with fluid flow in the exploration seismic frequency band (10 to 500 Hz).

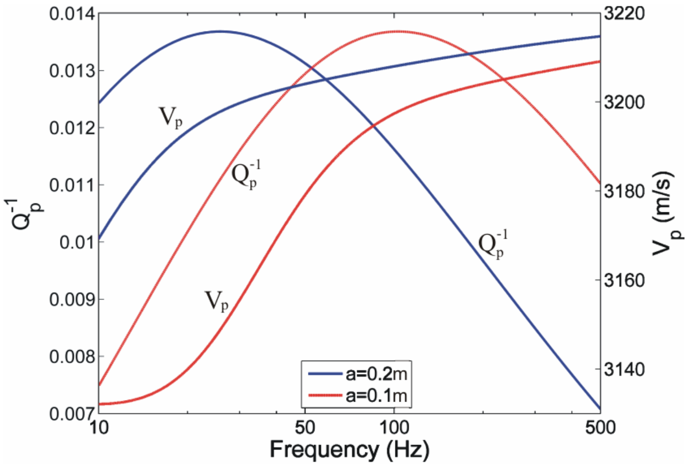

Figure 1: Attenuation and velocity dispersion in a random porous media with fluid flow in the 10 to 500 Hz band, with a being the characteristic length of inhomogeneities. Parameters: bulk modulus of mineral 40 GPa, bulk modulus of dry rock 4.5 GPa, bulk modulus of fluid 2.17 GPa; shear modulus 9 GPa; density of mineral 2.65 g/cm3, density of fluid 1 g/cm3; porosity 0.17, permeability 250 mD, and viscosity of fluid 0.001 Pa•s. After Müller and Gurevich (2005). Note that the frequency axis is in log scale.

Evidence of velocity dispersion has been provided by both laboratory and field experiments. The results have demonstrated that velocity dispersion may be a strong indicator of petrophysical properties. However, most of the existing velocity dispersion observations were in the sonic and ultrasonic frequency band, and do not provide enough information in the seismic frequency band, which is of great significance for exploration seismology. The range of seismic wavelength is from a few meters to a few hundred meters, which makes it possible to assess porosity, fractures, and fluid fill, etc, in a rock volume as a bulk rock property. So, if we can measure velocity dispersion, we will be able to establish a direct link between petrophysical properties and seismic data.

Method to Measure Velocity Dispersion in Seismic Frequency Band

Attenuation alters the shape of a signal's amplitude spectrum, whereas phase velocity dispersion changes the phase spectrum. Therefore, uncorrelated vibrator data are appropriate to measure the small velocity dispersion in the seismic frequency band. The advantages include (1) the ability to control or to measure both the amplitude and phase spectra of the pilot sweep; and (2) the retention of both the amplitude and phase spectra of the received sweep, which is no longer possible once the signal has been correlated.

In the transmission (VSP) geometry, when velocity dispersion is negligible, the received time-frequency (t-f) relation will be parallel to the pilot t-f relation. Otherwise, the received t-f relation will deviate. The difference between the pilot and the received t-f relations gives the frequency-dependent travel time, from which the dispersion of ray-path-average velocity can be calculated. We have developed a new method to measure the t-f relation in uncorrelated vibrator data with satisfactory accuracy and robustness (Sun and Milkereit, 2006).

Examples

The Mallik gas hydrate field is located in Mackenzie Delta, NWT, Canada (Dallimore et al. 2005). In general, the zone of interest consists of permafrost, water-saturated sediments, and gashydrate-bearing sediments. Three-component multi-offset vibrator VSP survey has been conducted at the 3L-38 Mallik gas hydrate research well. The uncorrelated vibrator data from this survey have been analyzed to determine the seismic attenuation and velocity dispersion in this area. Figure 2 shows the vertical component of the correlated VPS section, and the P-wave velocity from well logging. The source-borehole offset was 22m, and the receivers were in the 560 to 1145 m depth range.

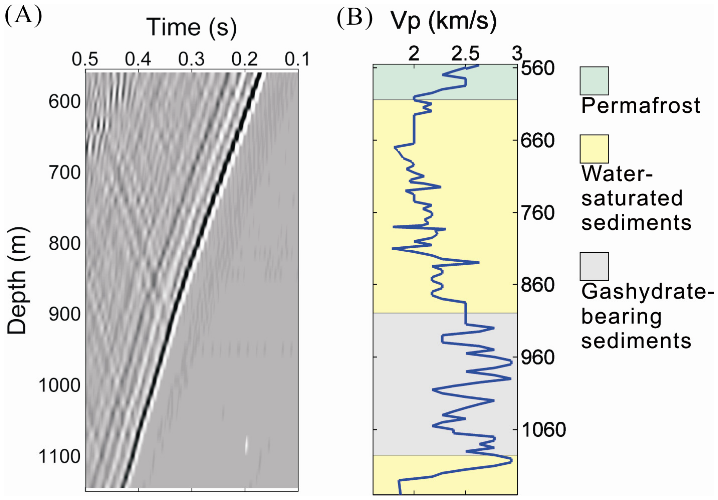

Figure 2: (A) The 0.1 to 0.5 s of the correlated vibrator VSP section from the 3L-38 Mallik gas hydrate research well, vertical component. The source-borehole offset was 22 m, and the depth range was 560 to 1145 m. (B) The P-wave velocity from well logging, compared with the approximate geological setting.

Using uncorrelated vibrator data, the observed velocity dispersion indicates that in general, seismic velocity is higher at a higher frequency (Sun et al, 2007). This trend can be explained with linear velocity dispersion, and a constant Q can be calculated. This Q estimate is consistent with that calculated from the spectral ratio method (Tonn, 1991). In addition to the linear velocity dispersion, narrow band velocity fluctuations exist.

The disadvantage of explaining the velocity dispersion data with simple straight line fit is that very limited information of petrophysical properties can be extracted. An alternative approach is to fit the velocity dispersion data to appropriate petrophysical models. As an example, for the Mallik data, a four-layered model has been established according to the geological setting. First, the velocity dispersion curves of different layers were calculated using a layer striping approach. Then, for each layer, the velocity dispersion curve was fitted to a petrophysical model. The parameters of this four-layered model are shown in Table 1. Model fits of the layers 1~3 are shown in Figure 3. Selection of the parameters is based on Lee (2002) and well logs from the Mallik gas hydrate research wells.

	Layer 1	Layer 2	Layer 3	Layer 4
Depth range (m)	0-600	600-900	900-1100	>1100
Petrophysical model 1. Müller and Gurevich (2005) 2. Mavko et al (1998)	Random porous medium with fluid flow [1] (permafrost)	Mavko-Jizba squirt flow [2] (sediments)	Random porous medium with fluid flow [1] (gashydrate)	(The same as Layer 2)
Bulk modulus of the mineral (GPa)	36	30	30	
Bulk modulus of dry rock (GPa)	8.9	3.5	3.7	
Bulk modulus of dry rock, high pressure (GPa)	N/A	4.5	N/A	
Bulk modulus of the fluid (GPa)	2.17	2.17	2.17	
Shear modulus (GPa)	6.8	1.7	3.6	
Density of the mineral (g/cm^3)	2.6	N/A	2.6	
Density of the fluid (g/cm^3)	1	N/A	1	
Density of rock (g/cm^3)	--	2.1	--	
Effective porosity	0.2	0.48	0.3	
Permeability (mD)	250	N/A	250	
Viscosity of the fluid (Pa•s)	0.001	N/A	0.001	
Characteristic length of inhomogeneities (cm)	10	5	8	

Table 1: Petrophysical parameters in the four-layered model to fit the velocity dispersion observations in the Mallik uncorrelated vibrator VSP data. The parameter selection was based on Lee (2002) and the well logs from Mallik gas hydrate research wells.

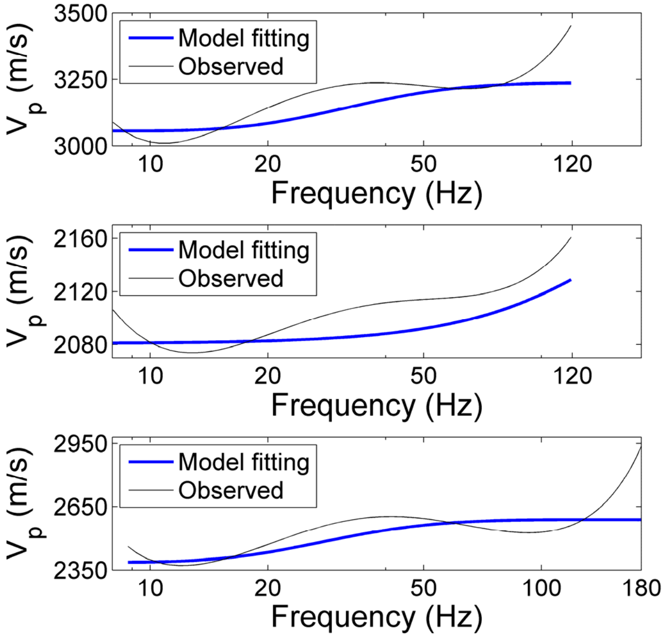

Figure 3: From top to bottom: velocity dispersion models of the layers 1, 2, and 3, respectively, for the Mallik data, compared with the observed velocity dispersion curves (smoothed) of each layer, using the parameters shown in Table 1. Note that the scales of velocity axes are different in the three plots, and the frequency axes are in log scale.

Figure 4 shows the model fitting for the velocity dispersion data observed in the uncorrelated vibrator sweep received at the depth 1085 m. Compared with the linear fitting, the model fitting not only mathematically better explains the data, but provides an opportunity to link to the bulk petrophysical properties of different layers.

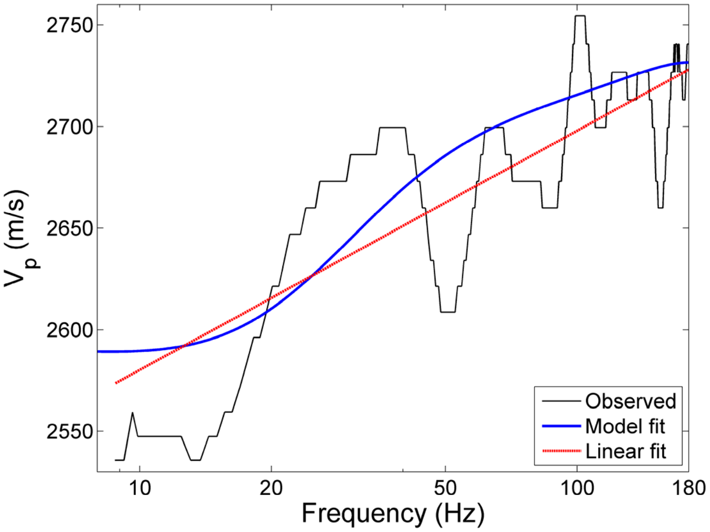

Figure 4: Model fitting of the observed velocity dispersion of in the vibrator sweep received at the depth 1085 m in Mallik data, compared with the linear fitting. Parameters of the layered model are shown in Table 1, and the velocity dispersion models of different layers are shown in Figure 3.

Conclusions

Attenuation and velocity dispersion in the seismic frequency band can be measured with satisfactory accuracy and robustness using uncorrelated vibrator data in VSP geometry. Linear fitting of velocity dispersion observations provides a Q estimate which is comparable to that from the classical spectral ratio method. Alternatively, the observed velocity dispersion data can be fitted using petrophysical models. For broadband seismic data, the velocity dispersion measurements can be used to fit more detailed attenuation models for porous or fractured media.

Acknowledgements

The Mallik 2002 Gas Hydrate Production Well Research Program was supported by the International Continental Scientific Drilling Program. L. Sun receives support from NSERC.

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